Promises and limitations of wavefront corrections with annular apertures using Scanning Laser Ophthalmoscopy

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Purpose

Similar to dark-field microscopy annular apertures may be introduced in ophthalmic instrumentation to eliminate low angular-scattering components. When used with coherent light, apodization of the incident beam with a central obstruction or conversion to an annular beam using beam-shaping techniques may be used to increase the effective numerical aperture and thus to squeeze down the width of the light at focus. For scanning retinal imaging applications this holds promise for improved resolution with an up to 60% increase of the ocular numerical aperture. In this study we discuss alternatives that may generate an annular illumination and show examples with scanning laser ophthalmoscopy images acquired by use of an annular incident beam created with a central stop [1]. The approach is discussed in relation to matching of the focused incident beam to the expected waveguide modes of individual cone photoreceptors [2]. The pros and cons of the scheme are discussed and requirements for wavefront correction with an annulus are established in relation to the retinal imaging application.

Methods

A scanning laser ophthalmoscope featuring a Badal defocus corrector and a 140 actuator MEMS deformable mirror (Boston Micromachines) with a 3.5 micron stroke has been constructed for retinal imaging using a 785 nm wavelength laserdiode and confocal detection by an APD. Image videos (up to 512×512 pixels) are acquired at 47 fps and subsequently cross-correlated for maximum stability during playback. Images have been acquired using different annuli with a 5 mm outer beam diameter to create a tighter focus of the scanning focused beam.

Results

The use of the annular illumination scheme has proven useful to explore light-to-cone photoreceptor coupling mechanisms for parafovea cones and for resolving of cones nearer the fovea centralis. Some examples of images obtained are shown in Fig. 1 below.

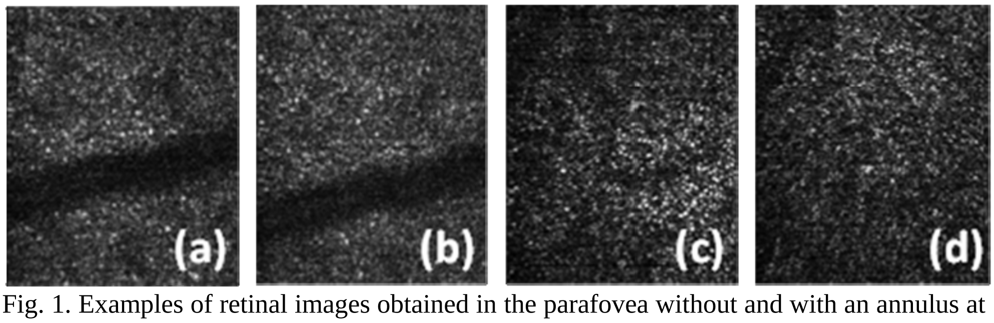

Fig. 1. Examples of retinal images obtained in the parafovea without and with an annulus at 10 degrees parafovea (a,b) and at 2 degrees from the fovea (c,d) using wavefront correction.

The results show that for the parafovea region where cone photoreceptors are large best results are obtained with a wide focus with the light confined within the acceptance angle (numerical aperture) of the cones. In turn, nearer the fovea centralis both wavefront correction and the added increase of the numerical aperture with the annulus can prove beneficial to better match the illumination to the smaller cones.

A limitation for the optimal functioning of the annular illumination is that the contributing wavefront needs to be accurately controlled across the entire annulus (for the incident beam) and across the entire unobstructed pupil (for the light backscattered by the retina). Thus, remnant aberrations can lower the attainable quality of the focus as shown for measured aberrations in Fig. 2.

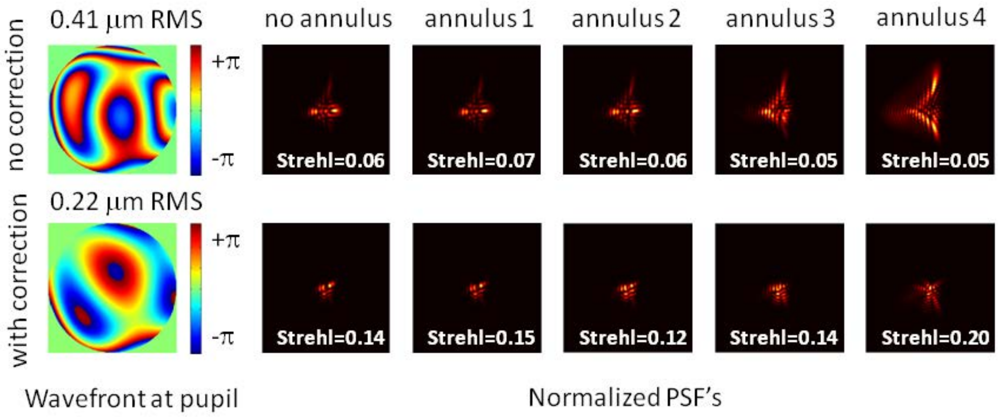

Fig. 2. Examples of measured ocular aberrations prior to and post wavefront correction in the scanning laser ophthalmoscope. The corresponding calculated point-spread-function images highlight also the intensity Strehl ratios. Annulus 1 to 4 correspond to a central stop of 1 to 4 mm for a 5 mm outer-diameter incident beam.

Conclusions

The use of the annular illumination scheme has proven useful to explore light-to-cone photoreceptor coupling mechanisms for parafovea cones and for resolving of cones nearer the fovea centralis. A limitation has been found in the remnant aberrations that with the wavefront correction used still remains notably lower than the diffraction limit. A remnant RMS aberration below $\lambda/10$ would be required across the pupil to obtain intensity Strehl ratios of 0.80 or higher.

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References

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2. B. Vohnsen, I. Iglesias, and P. Artal, "Guided light and diffraction model of human-eye photoreceptors," J. Opt. Soc. Am. A 22, 2318-2328 (2005).